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The JPL Low-Cost Silicon Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DoE.

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ANALYSIS AND EVALUATION OF PROCESSES AND EQUIPMENT IN TASKS II and IV of the LOW-COST SOLAR ARRAY PROJECT

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M. Wolf

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ABSTRACT

To facilitate the task of objectively comparing competing process options, a methodology was needed for the quantitative evaluation of their relative cost effectiveness. Such a methodology has now been developed and is described in this report, together with three examples for its application.

The criterion for the evaluation is the cost of the energy produced by the system.

The method permits the evaluation of competing design options for subsystems, based on the differences in cost and efficiency of the subsystems, assuming comparable reliability and service life, or of competing manufacturing process options for such subsystems, which include solar cells or modules. This process option analysis is based on differences in cost, yield, and conversion efficiency contribution of the process steps considered.

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1. INTRODUCTION

The manufacturing methods for photovoltaic solar energy utilization systems consist, in complete generality, of a sequence of individual processes. This process sequence has been, for convenience, logically segmented into five major "work areas": Reduction and purification of the semiconductor material, sheet or film generation, device generation, module assembly and encapsulation, and system completion, including installation of the array and the other subsystems. For silicon solar arrays, each work area has been divided into 10 generalized "processes" in which certain required modifications of the work-in-process are performed. In general, more than one method is known by which such modifications can be carried out. The various methods for each individual process are identified as process "options". This system of processes and options forms a two-dimensional array, which is here called the "process matrix".

In the search to achieve improved process sequences for producing silicon solar cell modules, numerous options have been proposed and/or developed, and will still be proposed and developed in the future. It is a near necessity to be able to evaluate such proposals for their technical merits relative to other known approaches, for their economic benefits, and for other techno-economic attributes such as energy consumption, generation and disposal of waste by-products, etc. Such evaluations have to be as objective as possible in light of the available information, or the lack thereof, and have to be periodically updated as development progresses and new information becomes available. Since each individual process option has to fit into a process sequence, technical interfaces between consecutive processes must be compatible. This places emphasis on the specifications

for the work-in-process entering into and emanating from a particular process option.

The objective of this project is to accumulate the necessary information as input for such evaluations, to develop appropriate methodologies for the performance of such techno-economic analyses, and to perform such evaluations at various levels.

This report describes a methodology for the objective comparative evaluation of competing subsystem design or manufacturing process options. The evaluation criterion is the cost of the energy delivered from the system. A requirement for the analysis is, that the subsystems or process options to be evaluated are functionally comparable. The evaluations are based on differences in cost and performance (efficiency) for the subsystem designs, and on differences in cost, efficiency contribution, and yield for manufacturing process options. Only relatively few, summary type of data are needed for these evaluations. Examples are the cost of the input work-in-process, the combined yields of all subsequent process steps, the total of all area-based costs except for the subsystem under consideration (e.g. the solar cell), etc. Service life, affecting depreciation, and reliability, which could express itself in differing maintenance costs, have been considered constant. Three examples of the application of the methodology are shown, two dealing with subsystem design variations. The first of these involves a variation in solar cell efficiency, the second variations in both solar cell efficiency and module packing factor. The third example shows a comparison of a 5-step process of pn-junction and BSF layer formation by diffusion with a 2-step process of ion-implantation accomplishing the same change in the work-in-process.

2. Technical Discussion

Methodology for Energy-Cost Effectiveness Evaluation of Subsystem Design and Manufacturing Process Options for Photovoltaic Solar Power Systems

Introduction.

One of the important attributes of a photovoltaic solar energy conversion system is its economic viability. The evaluation of this attribute is regularly performed in decision making about the use of such a system in a particular application, as well as in comparing the merits of one particular system design or solar cell production process against another. The key aspect in such an evaluation is the comparison of the cost of electrical energy produced by the photovoltaic system with the cost of competitively available electrical energy.

The unit cost c_{En} of the electrical energy delivered from the photovoltaic system can be expressed, following ref. (1), as:

$$c_{En} = \frac{C_{op} + \gamma_{cap} C_{cap}}{E_{Ld}} \; ; \; [\$ \; kWh^{-1}] \qquad (1)$$

where C_{op} are the annual operating costs [$ y^{-1}], C_{cap} is the capital spent in acquiring the system [$] and γ_{cap} is the equivalent annual cost of capital [y^{-1}]. This equivalent annual cost of capital may, outside of the usual components of interest, taxes, depreciation, etc., include such considerations as desired profit, present or discounted value of life cycle costs, inflation adjustments, etc. As the "fuel" in a solar energy utilization system is "free", the operating costs are essentially reduced to the maintenance costs, at least for the smaller distributed systems. And since it is generally assumed, in the absence of information to the contrary, that the systems will be designed and built for high reliability and thus require little maintenance, the maintenance costs are usually neglected in comparison to the costs of the capital. E_{Ld} is the electrical energy usefully delivered during a year from the photovoltaic system to the load.

Thus:

$$c_{En} \approx \gamma_{cap} \frac{c_{cap}}{E_{Ld}} = \gamma_{cap} \cdot \Gamma \ ; \ [\$ \ kWh^{-1}] \qquad (2)$$

$$\Delta c_{En} = \frac{c_{cap}}{E_{Ld}} \cdot \Delta \gamma cap$$

As γ_{cap} is a constant for a particular company at a given time, but will differ from company to company, the system dependent energy cost determinator is really the quantity:

$$\Gamma = \frac{C_{cap}}{E_{Ld}} \ ; [\$ \ kWh^{-1} \ y] \qquad (3)$$

which is the ratio of the required investment to the energy delivered per year. The evaluation and optimization of this quantity is therefore of primary interest.

The Energy Delivered to the Load.

The energy E_{Ld} delivered during the year to the load is clearly related to, although different from, the energy E_o delivered by the photovoltaic array itself to the remainder of the system. For a photovoltaic array of total exposed area $A_{Ar}[m^2]$, E_o is given by:

$$E_o = A_{Ar} \int_0^{8760h} H(t) \ \eta_{Ar} \ (H(t), \ T(t)) \ \phi(t) \ dt; \ [kWh \cdot y^{-1}] \qquad (4)$$

where η_{Ar} (H(t), T(t)) is the effective array efficiency in the time interval dt around time t, with η_{Ar} being dependent on the temperature T(t) of the array and on the irradiance H(t) $[kW \ m^{-2}]$ during that time interval, as well as on the varying spectral distribution and the angle of incidence of the light. $\phi(t)$ is a factor of magnitude between zero and one, which describes whether, or how much, energy can be delivered by an array for transfer to the load or to storage, depending on the existence of load and on the status of the storage system during the respective time interval. Eq. (4), being a definite integral, can be expressed as:

$$E_o = A_{Ar} H_{pk} \; \eta_{Ar,\,std} \; f_{Ld} \cdot 8760; [\mathrm{kWh \cdot y^{-1}}] \qquad (5)$$

following the custom of referring the output to "nameplate rating", or peak power output capability, which is, for the solar array, expressed by the product of the expected peak irradiance H_{pk} and the array efficiency $\eta_{Ar,\,std}$ measured under standardized conditions (including the peak irradiance H_{pk}). The connection to eq. (4) is made via the "load factor" f_{Ld} which is the ratio of the output actually delivered during the year to the "nameplate rating." f_{Ld} is usually determined from the results of a system simulation computer run for a one-year period, which includes the solar energy availability statistics - normally weather bureau data for a selected year - and the expected load statistics. Ideal would be a simulation run over the system life to determine an f_{Ld} value which represents the average over the system life. However, forward looking solar energy availability data do not exist, and even forward looking load statistics will be of doubtful validity. A compromise could be a backward looking simulation over a period equal in duration to the system life, using real data. The limited gain in confidence, however, generally does not justify the additional expense. A one-year run is usually felt necessary to properly include the seasonal changes and the short term meteorological variations.

The total number of hours in the year (8760 h), multiplied by the load factor f_{Ld} represent an "equivalent time" t_{eq} during which the array could have operated at peak power capability to produce the same amount of energy as actually delivered. It is additionally useful to define the quantity p_{pk}, the peak power output capability per unit area of the array, which is simply:

$$p_{pk} = H_{pk} \cdot \eta_{Ar,std}; \; [\mathrm{kW\ m^{-2}}] \qquad (6)$$

The energy $E_{Ld,dir}$ delivered from the array directly to the load will generally be less than E_o, being reduced by the power conditioning subsystem efficiency η_{PC}, and by the fraction f_{St} of the annual array output which is, in the average, transferred into the storage subsystem :

$$E_{Ld,\ dir} = E_o\ (1 - f_{St}) \cdot \eta_{PC};\ [kWh \cdot y^{-1}], \qquad (7)$$

In addition, the energy $E_{Ld,St}$ is delivered from the storage subsystem, to the load:

$$E_{Ld,St} = E_o f_{St}\ \eta_{St}\ \eta_{PC};\quad [kWh \cdot y^{-1}] \qquad (8)$$

where η_{St} is the efficiency of the storage subsystem.
In the relationship of eq. (7), the assumption is made that all power conditioning occurs after storage. Otherwise, the efficiency η_{PC} would have to be broken into several terms.

Summing eq. (7) and (8) yields then the total energy E_{Ld} delivered to the load:

$$E_{Ld} = E_o\ [1 - f_{St}\ (1 - \eta_{St})]\ \ \eta_{PC};\ [kWh \cdot y^{-1}] \qquad (9)$$

The expression in the brackets, which is a function of the load curve relative to the solar energy availability curve, as well as of system design, incl. type and capacity of the storage device, could be represented by a "storage transfer factor" τ_{St}, so that eq. (9) can be written as:

$$E_{Ld} = E_o \cdot \tau_{St} \cdot \eta_{PC};[kWh\ y^{-1}] \qquad (9a)$$

It has to be noted that the load factor f_{Ld}, included in E_o, is also dependent on the same variables as τ_{St}, and generally increases with increasing f_{St} and η_{St}.

The system power delivery capability P_{sy} which is usually limited by the power conditioning subsystem and/or the storage subsystem capacities, can be related through the factor f_{Po} to the array peak power capability:

$$P_{Sy} = A_{Ar} P_{pk} \cdot \tau_{St} \cdot \eta_{Pc} \cdot f_{Po}; \quad [kW] \tag{10}$$

The factor f_{Po} may be smaller or greater than unity.

The storage subsystem capacity can illustratively be expressed by the "equivalent storage time" t_{St} which is the time interval for which the storage device, when originally fully charged, could provide energy at the peak system power delivery rate, until discharged to a predetermined minimum charge state:

$$E_{st} = P_{sy} \cdot t_{St}; \quad [kWh] \tag{11}$$

Evaluation of the Energy-Cost Effectiveness of Competing Subsystem Options.

The entire photovoltaic solar energy conversion system is composed of a network of subsystems, basically connected in series according to the energy flow, as indicated in Fig. 1. The individual subsystems may be defined in any way which facilitates the system analysis or the cost determination. Thus, a foundation for the solar array may be considered a subsystem, as a circuit breaker for system protection, or a battery for energy storage may be. Clearly, the entire system cost is the sum of all the individual subsystem costs C_i:

$$C_{cap} = \sum_{i=1}^{N} C_i; [\$] \tag{12}$$

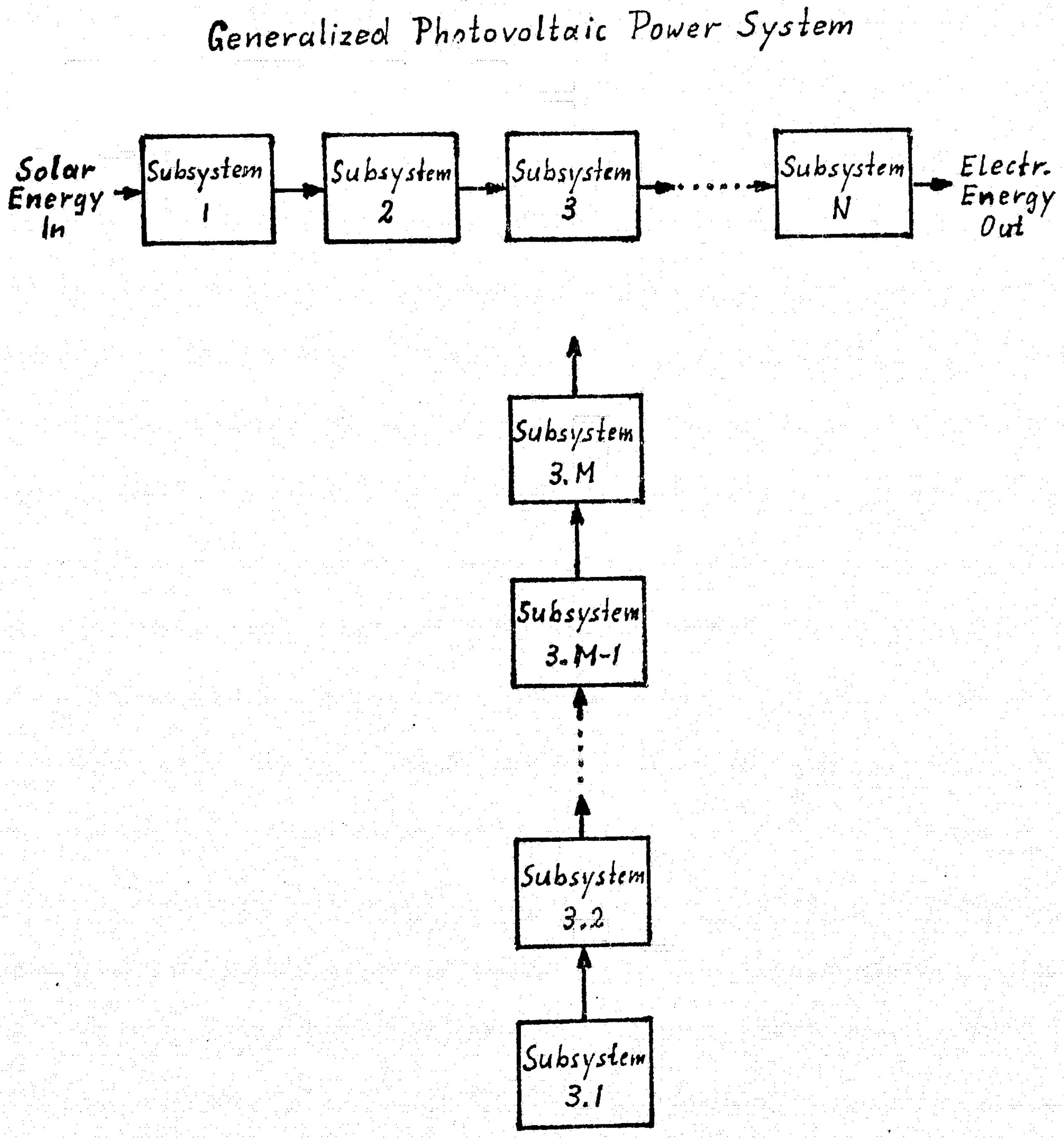
Generalized Photovoltaic Power System
Solar Energy In
Subsystem 1
Subsystem 2
Subsystem 3
Subsystem N
Electr. Energy Out
Subsystem 3.M
Subsystem 3.M-1
Subsystem 3.2
Subsystem 3.1

Fig. 1.

and the system performance is a function of the performance of all the subsystems. Frequently, some subsystems are not directly in the line of energy flow, as indicated in Fig. 1 by subsystems 3.1 to 3.M. For an evaluation as discussed here, it is best to combine these into a "subsystem group" which, as a whole, is in the line of energy flow. The cost of the subsystem group is then the sum of the costs of the subsystems within the group. The evaluation of the cost effectiveness of an individual subsystem of the group can be performed by expansion of the methodology outlined here.

In general, both cost and performance of a subsystem are the result of an engineering design trade-off in which the performance characteristics of available devices and their commercial prices are considered, as well as the subsystem complexity and assembly cost. It is the purpose of this section to outline a methodology for assessing the cost effectiveness of such trade-offs from the viewpoint of the cost of the energy produced by the system.

Since the entire system (Fig. 1) can be viewed as a series connection of subsystems i or groups of subsystems, its efficiency can be expressed as the product of the efficiencies η_i' of the individual subsystems or groups of subsystems:

$$\eta_{syst} = \eta_{Ar,std} \cdot \tau_{St} \cdot \eta_{PC} \cdot f_{Ld} = \prod_{i=1}^{N} \eta'_i ; \tag{13}$$

or

$$\eta_{syst} = f'_{Ld} \prod_{i=1}^{N} \eta_i ; \tag{13a}$$

Representation (13) is a generalization to the subsystem level of the expression contained in eq. (9a) where the η'_i include all the contributions contained in the efficiencies $\eta_{Ar,std}$, η_{PC}, and in the quasi-efficiencies τ_{St} and f_{Ld}. In the second version (eq. (13a)), the η_i factors contain all the direct efficiency-like influences of each of the subsystems, while all indirect, or second-order influences are relegated to the "reduced load factor" f'_{Ld}. The application and practicality of this approach will be recognized later in this paper.

These subsystem efficiencies have an impact on the dimensioning of the individual subsystems, and consequently on their costs, since the system has to be designed to satisfy a given load by supplying a certain E_{Ld}. Thus, subsystems placed nearer the beginning of the series connected subsystem chain have to be dimensioned relatively larger to account for the losses of subsequent subsystems. This principle is recognizable in eq. (9a) where the array output E_o is larger by the inverse of the product $f_{PC} \cdot \tau_{St}$ than the energy E_{Ld} which is delivered to the load.

The division into subsystems can be practically pursued to the smallest, separately identifiable, functional units with their individual efficiencies. This shall be illustrated by example of the photovoltaic array, with its array efficiency $\eta_{Ar,\ std}$, which is frequently considered as composed of "subarrays" which are made up of "modules". The module contains a group of solar cells (a subsystem) which have an average efficiency $\overline{\eta}_{Ce,\ std}$. In series/parallel connecting these cells of slightly differing characteristics into a "matrix" (a subsystem), a small loss in potential power output is incurred, expressed in the " matrixing efficiency" η_{Ma}. The interconnect wiring in this matrix is another separately identifiable subsystem with its

Joule losses, which are accounted for in the "wiring efficiency" η_{Wi}. The encapsulation forms two functional subsystems. The first is the window, including adhesive or pottant, with its optical transmission losses, leading to the encapsulation efficiency η_{En}. The second performance influencing attribute of the encapsulation is the heat transfer to the environment which determines the operating temperature of the array which controls the instantaneous operating efficiency of the module. This effect produces an "average annual cooling effectiveness factor" f_{Co}, a quasi-efficiency which usually is included in the load factor f_{Ld}. At the subarray (subscript SA) and the array (subscript Ar) levels, matrixing and wiring losses are again incurred, so that the cell energy output will have to be:

$$E_{Ce} = \frac{E_o}{\eta_{Ma}\ \eta_{Wi}\ \eta_{En} \cdot \eta_{Ma,SA}\ \eta_{Wi,SA} \cdot \eta_{Ma,Ar}\ \eta_{Wi,Ar}};\ [\mathrm{kWhy}^{-1}] \qquad (14)$$

The installation of the subarrays forms another subsystem which influences system performance twofold: through the subarray orientation, which may include one-or-two-dimensional tracking, and through the cooling effectiveness. Both of these attributes form quasi-efficiency factors which are part of the load factor f_{Ld}.

Since the orientation/tracking effect is a direct influence which can, under exclusion of variable atmospheric effects, be analytically evaluated, it can be beneficial to eliminate this performance factor from the (reduced) load factor and attach it as an efficiency factor to the installation (or tracking) subsystem.

Formally applying these principles by combining eq. (5), (9a), and (13), yields an expression for the energy delivered to the load, E_{Ld}, in terms of the subsystem efficiencies and quasi-efficiencies η_i':

$$E_{Ld} = H_{pk} \cdot A_{Ar} \cdot 8760 \prod_{i=1}^{N} \eta_i' \; [\mathrm{kWhy}^{-1}] \tag{15}$$

Introducing this expression together with eq. (12) into eq. (3) gives the energy cost determinator Γ in terms of subsystem cost and performance data, and constants, only:

$$\Gamma = \frac{1}{H_{pk} A_{Ar} 8760} \cdot \frac{\sum_{i=1}^{N} C_i}{\prod_{i=1}^{N} \eta_i'} \; ; \; [\$ \; \mathrm{kWh}^{-1} \mathrm{y}] \tag{16}$$

Following the approach used by Redfield in his "cost/Watt optimization" (2), the parameters of a single subsystem or subsystem group k of interest can be isolated in eq. (16):

$$\Gamma = \frac{1}{H_{pk} \cdot A_{Ar} \cdot 8760} \cdot \frac{\sum_{i=1}^{k-1} C_i + C_k + \sum_{i=k+1}^{N} C_i}{\prod_{i=1}^{k-1} \eta_i' \cdot \eta_k' \cdot \prod_{i=k+1}^{N} \eta_i'} \; ; \quad [\$ \; \mathrm{kWh}^{-1} \mathrm{y}] \tag{17}$$

or:

$$\Gamma = \frac{1}{H_{pk} \cdot A_{Ar} \cdot 8760} \cdot \frac{\sum_{i \neq k} C_i}{\prod_{i \neq k} \eta_i'} \cdot \left(\frac{1 + \frac{C_k}{\sum_{i \neq k} C_i}}{\eta_k'} \right) ; \; [\$ \; \mathrm{kWh}^{-1} \mathrm{y}] \tag{17a}$$

The expressions $\sum\limits_{i\neq k}$ and $\prod\limits_{i\neq k}$ stand for the sum or product, respectively, over all values of i from 1 to N, except for the value k. This form of Γ permits the evaluation of various design options for the same subsystem, or group of subsystems, with differing costs and efficiencies, with respect to their influence on the cost of the energy produced. Such an evaluation is particularly simple, if only C_k' and η_k are variables of the design options. Then, a first order Taylor expansion yields:

$$\Delta\Gamma = B \cdot \left\{ \frac{\dfrac{\Delta C_k}{\sum\limits_{i\neq k} C_i}}{\eta'_k} - \frac{\left(1 + \dfrac{C_k}{\sum\limits_{i\neq k} C_i}\right) \Delta\eta_k}{{\eta_k'}^2} \right\} \quad [\$kWh^{-1}y] \tag{18}$$

where ΔC_k and $\Delta\eta_k'$ are - positive or negative - differences against the base case in subsystem cost and efficiency, respectively, which result from the change in design of subsystem k. The constant B in eq. (18) is the product of the first two of the three terms on the right hand side of eq. (17a). A negative $\Delta\Gamma$ indicates a reduction in energy cost, and consequently a design improvement. It is readily apparent from eq. (18) that cost reductions and efficiency decreases counteract each other.

The condition imposed for the derivation of eq. (18), that only C_k and η'_k are variables of the design options, is in apparent conflict with several statements made in the preceding discussion. Thus, the load factor can be affected by changes in the system efficiency, particularly by changes in the storage transfer factor τ_{st}. To make the evaluations tractable, it is practical to proceed iteratively by considering the reduced load factor f'_{Ld} as temporarily constant and re-evaluating it only after several changes in the efficiencies. This procedure illuminates the need for the definition of a "reduced load factor"

f'_{Ld} according to eq. (13a) which contains only second order effects of the efficiencies and quasi-efficiencies. The iteration is frequently speeded by reinforcing properties of the second order effects. For instance, efficiency improvements tend, at constant E_{Ld}, to result in increased load factors.

The condition for the validity of eq. (18) further requires that C_k and η_k are independent of the designs of the other subsystems, and particularly that the design choice of subsystem k does not influence costs and efficiencies of the remaining subsystems. This condition can, in principle, always be fulfilled by judicious choice of the designation "subsystem k", so that interdependent parts of the system are included in the same subsystem.

A change in the efficiency of one subsystem affects, however, the system as a whole. While the resulting change in output energy E_{Ld} is appropriately accounted for in Γ , one or more of the subsystems subsequent to the changed subsystem in the chain may now be over- or underdimensioned, and the load may no longer be supplied as desired. This problem requires considering the system of concern in somewhat more detail.

The majority of the functional subsystems of a photovoltaic solar energy conversion system are basically modular and thus essentially without economics of scale, at least within the range of concern in an individual design tradeoff study. The costs of these subsystems can therefore be expressed as a unit cost times a quantity factor. Such quantity factors are the array area A_{Ar}, the power handling capacity P of some subsystems, and, for some energy storage related subsystems, the energy capacity E. Generalizing the usage in ref (1) and (2), the system cost can then be expressed as:

$$C_{cap} = \sum_k A_k \; c_{A,k} + \sum_\ell P_\ell \; c_{P,\ell} + \sum_m E_m \; c_{E,m} + \sum_n C_{F,n}; \; [\$] \qquad (19)$$

The area-based unit costs $C_{A,k}$ apply to the array related subsystems, including its installation and land costs. The power-based unit costs $c_{P,\ell}$ are connected with the power conditioning and other power handling equipment, although a part of the costs of the energy storage subsystems can also be proportional to power, for instance through the charge or discharge rates. The energy-based unit costs $c_{E,m}$ are concentrated in the storage subsystem. The remaining costs, including the system-status sensors and the control logic, represent the "fixed" costs, $C_{F,n}$.

Using this expression (19) for the capital costs in the energy cost determinator eq. (16), and simultaneously extracting the iteratively constant reduced load factor f'_{Ld}, from the efficiency product $\prod_i \eta_i$, yields the form:

$$\Gamma = \frac{1}{H_{pk} \cdot 8760 \cdot f'_{Ld}} \cdot \frac{\sum_{i=1}^{N} \left\{ \frac{A_i}{A_{Ar}} c_{A,i} + \frac{P_i}{A_{Ar}} c_{P,i} + \frac{E_i}{A_{Ar}} c_{E,i} + \frac{1}{A_{Ar}} C_{F,i} \right\}}{\prod_{i=1}^{N} \eta_i} ; \qquad [\$ \; kWh^{-1} y] \quad (20)$$

It will be observed that, in general, for every index i in the sum, only one of the unit cost factors $c_{A,i}$, $c_{P,i}$, $c_{E,i}$, or $C_{F,i}$ will be unequal to zero. An exception to this rule is known to exist in certain advanced storage batteries whose price is based on a combination of energy and power rating. Also, power conditioning subsystem groups may contain fixed cost subsystems, such as control elements.

In considering the quantity factors A_i, P_i, and E_i, several possible simplifications are immediately noticeable. First, all area based unit costs are commonly related either to the array area or to the solar cell area. The

latter is connected to the array area through the packing factor $f_{Pg} < 1$:

$$A_{Ce} = f_{Pg} \cdot A_{Ar} \; ; \quad [m^2] \tag{21}$$

Second, eq. (11) relates E_i to P_{Sy} through the equivalent storage time, and thus permits combined treatment of the second and third terms of eq. (20). Third, the dimensioning of each subsystem i of power dependent cost in the chain is determined by the system output specifications and the efficiencies of the subsystems subsequent to i in the direction of energy flow, so that:

$$P_i = \frac{P_{Sy}}{\prod\limits_{\ell = i+1}^{N} \eta_\ell} \; ; \quad [kW] \tag{22}$$

This permits expressing eq. (20), under use of eq. (6), (10), (11), (13a), and (21), and under application of the subscript Ce to the cell area based costs, Ar to the array area based costs, as:

$$\Gamma = \sum_{i=1}^{N} \left\{ \frac{1}{H_{pk} \cdot 8760 \cdot f'_{Ld}} \; \frac{f_{Pg} \cdot c_{Ce,i} + c_{Ar,i}}{\prod\limits_{\ell=1}^{N} \eta_\ell} + \frac{f_{Po}}{8760 \cdot f'_{Ld}} \; \frac{c_{P,i} \; (1 + t_{St,i})}{\prod\limits_{\ell = i+1}^{N} \eta_\ell} + \frac{1}{E_{Ld}} \; C_{F,i} \right\} ;$$

$$[\$ \; kWh^{-1} y] \tag{23}$$

where $t_{St,i}$ is zero or t_{St}, depending on the existence of an energy based cost contribution in subsystem i. The fixed costs, shown in the third term in the brackets of eq. (23), contribute to the energy costs independently of the subsystem's or the system's performance. They are also the only ones ex-

hibiting any direct economics of scale.

The first term in the bracket of eq. (23) can be evaluated for the impact of design options for an individual subsystem k in complete analogy to eq. (17) to (18). The second term, however, requires a slightly different treatment:

$$\sum_{i=1}^{N} \left(\frac{c_{P,i}}{\prod_{\ell=i+1}^{N} \eta_\ell} \right) = \sum_{i=1}^{k-1} \left(\frac{c_{P,i}}{\prod_{\ell=i+1}^{N} \eta_\ell} \right) + \frac{c_{P,k}}{\prod_{\ell=k+1}^{N} \eta_\ell} + \sum_{i=k+1}^{N} \left(\frac{c_{P,i}}{\prod_{\ell=i+1}^{N} \eta_\ell} \right) \qquad (24)$$

Consequently, first order Taylor expansion of eq. (23) yields the total cost-effectiveness criterion $\Delta\Gamma_k$ for a design change of subsystem k:

$$\boxed{\begin{aligned} \Delta\Gamma_k = \; & \Gamma_{A,i\neq k} \left[\frac{\Delta(f_{Pg} \cdot c_{Ce,k}) + \Delta c_{Ar,k})}{C_{A,\, i\neq k}} - \frac{\Delta\eta_k}{\eta_k} \left(1 + \frac{f_{Pg} c_{Ce,k} + c_{Ar,k}}{C_{A,\, i\neq k}} \right) \right] \\ & + \Gamma_{P,\, i<k} \left[\frac{\Delta[c_{P,k}\,(1 + t_{St,i})]}{C_{P,\, i<k} \cdot \prod_{\ell=k+1}^{N} \eta_\ell} - \frac{\Delta\eta_k}{\eta_k} \right] \\ & + \Gamma_{F,\, i\neq k} \frac{\Delta C_{F,k}}{C_{F,\, i\neq k}} \; ; \quad [\$ \text{ kWh}^{-1} \text{ y}] \qquad (25) \end{aligned}}$$

where:

$$\Gamma_{A,\, i\neq k} = \frac{1}{H_{pk} \cdot 8760 \cdot f'_{Ld} \prod_{\ell=1}^{N} \eta_\ell} \sum_{\substack{i=1 \\ \text{but } i\neq k}}^{N} (f_{Pg}\, c_{Ce,i} + c_{Ar,i}) \; ;$$

$$[\$ \text{ kWh}^{-1} \text{ y}] \qquad (26a)$$

$$\Gamma_{P,\ i<k} = \frac{f_{Po}}{8760 \cdot f'_{Ld}} \sum_{i=1}^{k-1} \frac{c_{P,i}\ (1 + t_{St,i})}{\prod_{\ell=i+1}^{N} \eta_\ell} \ ; \ [\$\ kWh^{-1} y] \qquad (26b)$$

and:

$$\Gamma_{E,i\neq k} = \frac{1}{E_{Ld}} \sum_{\substack{i=1 \\ \text{but } i\neq k}}^{N} C_{F,i} \ ; \quad [\$\ kWh^{-1}\ y] \qquad (26c)$$

are the respective "investment per (unit energy per year)" ratios for all subsystems, except subsystem k, with area based unit costs, combined; for all subsystems preceding subsystem k in the chain, with power or energy based unit costs, combined; and for all subsystems, except subsystem k, with fixed subsystem costs, combined. Correspondingly defined are the total subsystem investments:

$$C_{A,\ i\neq k} = \sum_{\substack{i=1 \\ \text{but } i\neq k}}^{N} (f_{Pg} \cdot c_{Ce,i} + c_{Ar,i})_i \quad [\$] \qquad (27a)$$

$$C_{P,\ i<k} = \sum_{i=1}^{k-1} \frac{c_{P,i}\ (1 + t_{St,i})}{\prod_{\ell=i+1}^{N} \eta_\ell} \ ; \quad [\$] \qquad (27b)$$

and

$$C_{E,\ i\neq k} = \sum_{\substack{i=1 \\ \text{but } i\neq k}}^{N} C_{F,i} \ ; \quad [\$] \qquad (27c)$$

which represent the combined normalized costs of all subsystems, except subsystem k, with area based unit costs; of all subsystems preceeding subsystem k in the chain, with power or energy based unit costs; and of all subsystems, except subsystem k, with fixed subsystem costs; respectively. Examples of the application of eq. (25) are shown in the section entitled: "Examples of Application of the Methodology."

It is interesting to note that the three terms in the "cost effectiveness criterion" $\Delta\Gamma_k$ contain the "investment per (energy per year)" ratios for the remainder of the system, multiplied by the difference between two terms which are based on the relative cost change and the relative efficiency change, respectively. It is to be noted, however, that the relative cost change is based on the cost of the remainder of the system, while the relative efficiency change is based on the efficiency of the subsystem under evaluation. The expression "remainder of the system" refers here to the subsystems with equally based unit costs, and, in the case of power or energy based unit costs, only to the subsystems preceding in the chain the subsystem being evaluated. For the "fixed cost subsystems", there is no efficiency influence.

It may also be noted that the cost-effectiveness criterion (eq. (25)) contains the terms

$$\Delta\Gamma_k = -\frac{\Delta\eta_k}{\eta_k} \left(\Gamma_{A,\ i\neq k} + \Gamma_{P,\ i<k} \right) + \ldots \quad [\$\ \mathrm{kWh}^{-1} \mathrm{y}]$$

where the relative efficiency change of subsystem k can refer to a subsystem of power based unit cost, but influence the cost-effectiveness through the subsystems of area based cost structure, or vice versa. The latter, inverse case is, however, not likely to occur as a subsystem of power based unit cost is rarely followed by a unit area cost based subsystem in the photovoltaic power system chain.

The "cost effectiveness criterion" $\Delta\Gamma_k$ permits the evaluation of various subsystem design options both with respect to their benefit (or harm) in comparison to a baseline design, through the sign of $\Delta\Gamma_k$, and with respect to the relative merits of the different options, through the magnitude of $\Delta\Gamma_k$. "Optimizations", that is a search for $\Delta\Gamma_k = 0$ as discussed in ref. (2), will, with very few exceptions, not be possible, since the relationships between cost and performance are usually not available in functional form and, moreover, seem always to be limited by the contemporary, and often rapidly changing status of technology. "Relative evaluations", as discussed here, applied to specific subsystem design options, are, however, readily performed.

The method is easy to apply, since for the subsystem to be evaluated, only the cost and performance differences against a baseline design have to be known, and since the other needed inputs involve only a few summary data on the remainder of the system. While it may be, in some cases, difficult to obtain exact data for the remainder of the system, intelligent estimates will frequently suffice. When such estimates are used for the cost of the remainder of the system, error estimates should be made, as mis-estimation of the cost could shift the relative impact of the competing terms involving the subsystem cost - and efficiency - changes.

Evaluation of the Cost-Effectiveness of Manufacturing Process Options.

While many of the subsystems in a photovoltaic solar energy system are assembled of standard components by common methods, the solar cells, their assembly into arrays, and at a later time perhaps also the energy storage device, are specially manufactured items which represent a significant part of the total system cost. Since producing these devices with their highest possible performance at the lowest price is the fundamental condition for

success in large scale introduction of photovoltaic solar energy systems, comparative evaluations of the various available options for each step of the manufacturing process sequence need to be performed. A methodology very similar to that outlined for evaluation of the subsystem design options can be applied for this purpose.

Evaluation methodologies for the solar cell and the module manufacturing processes are of greatest current interest. Both of these "subsystems" have an area based unit cost structure, and can therefore be treated by the same approach. The quantity to be reduced as far as possible is the "investment per (unit energy per year)" Γ (eq. (23)) which can be expressed as the sum of various sub-gammas for the different subsystems:

$$\Gamma = \sum_{i=1}^{N} (\Gamma_{A,i} + \Gamma_{P,i} + \Gamma_{F,i}); \quad [\$ \ kWh^{-1} y] \tag{28}$$

where that for the subsystems of area based unit costs has the form:

$$\Gamma_{A,i} = \frac{1}{H_{pk} \cdot 8760 \cdot f'_{Ld}} \frac{(f_{Pg} \, c_{Ce,i} + c_{Ar,i})}{\prod_{\ell=1}^{N} \eta_\ell}; \quad [\$ \ kWh^{-1} \ y] \tag{29}$$

As the solar cells and the modules are among the first subsystems in the chain, and are not preceded by power based subsystems, only the $\Gamma_{A,i}$ terms need to be considered for an evaluation of the manufacturing processes for one of these two subsystems. Thus, for the solar cells as subsystem k, it is:

$$\Gamma_A = (\Gamma_{A,\ i \neq k} \cdot \eta_k) \frac{1}{\eta_k} + \frac{f_{Pg}}{H_{pk} \cdot 8760 \cdot f'_{Ld} \cdot \prod_{\ell=1,\ \text{but}\ \ell \neq k}^{N} \eta_\ell} \cdot \frac{c_{Ce,k}}{\eta_k};$$

$$[\$ \ kWh^{-1} \ y] \tag{30}$$

using eq. (26a) for simplification. The product in the parenthesis of the first term is independent of subsystem k.

The fabrication process sequence for subsystem k, the solar cells, shall be composed of P process steps, with the individual step p costing $c_{Ce,k,p}$ on the basis of unit area of good work-in-process (partly processed solar cells) leaving the process station. The subsystem cost $c_{Ce,k}$, however, is based on the area of the finished, good cells leaving the end of the solar cell production line. Since each process step is afflicted with a certain yield y_p, the amount of solar cell area to be processed through step p has to be increased above the finished cell area to make up for the yield losses of the subsequent process steps. Consequently, the unit cell area cost of the subsystem k can be expressed as:

$$c_{Ce,k} = \sum_{p=1}^{P} \frac{c_{Ce,k,p}}{\prod_{\ell=p+1}^{P} y_\ell} ; \quad [\$ \ m^{-2}] \tag{31}$$

For solar cells, it has been long-standing practice[3] to calculate an idealized, theoretical "limit efficiency" $\eta_{k,Lim}$ and to gauge the success in design and fabrication of the "real" solar cells by determining the various "loss factors" ϕ which describe the degree of approach to ideality for the identified, efficiency influencing parameters. In variation of this practice, Redfield (2) assigned a loss factor to each of the process steps to facilitate his "cost/Watt" evaluation. Adapting this practice, the efficiency of the subsystem k can be expressed as a limit efficiency times a product of loss factors.

$$\eta_k = \eta_{k,Lim} \prod_{p=1}^{P} \phi_{k,p} ; \tag{32}$$

Each of the loss factors $\phi_{k,p}$ is attributed to a step in the serial sequence of process steps, and it expresses, by being normally less than unity, the degree to which the individual process step causes the subsystem performance to deviate from ideality. Different competing process options can usually be expected to cause different degrees of deviation from ideality. While for solar cells, a limit efficiency near 0.25 is usually discussed, for the module or panel assembly, a limit efficiency of unity will be practical to assume.

Making use of eq. (27a), (29), (31), and (32) permits expressing eq. (30) in a form more conducive to derivation of the cost-effectiveness criterion:

$$\Gamma_A = \frac{(\Gamma_{A,i\neq k} \cdot \eta_k)}{\eta_{k,lim} \prod\limits_{\substack{p=1 \\ \text{but } p\neq n}}^{P} \phi_{k,p}} \; \frac{1}{\phi_{k,n}} \left\{ 1 + \frac{f_{Pg}}{C_{A,i\neq k}} \left[\sum_{p=n+1}^{P} \left(\frac{c_{Ce,k,p}}{\prod\limits_{\ell=p+1}^{P} y_\ell} \right) + \frac{c_{Ce,k,n}}{\prod\limits_{\ell=n+1}^{P} y_\ell} + \frac{1}{y_n} \sum_{p=1}^{n-1} \left(\frac{c_{Ce,k,p}}{\prod\limits_{\substack{\ell=p+1 \\ \text{but } p\neq n}}^{P} y_\ell} \right) \right] \right\}; [\$ \text{ kWh}^{-1} \text{ y}] \tag{33}$$

In this form, the three characteristic attributes $\phi_{k,n}$, Y_n, and $c_{Ce,k,n}$ of process step n which is the step to be evaluated, have been isolated. Applying again a first order Taylor expansion to the investment per (energy per year) ratio, this time based on eq. (28) and (33), yields the cost effectiveness criterion $\Delta\Gamma$ for the individual solar cell manufacturing process step n :

$$\boxed{\Delta\Gamma_{k,n} = \Gamma_{A,i\neq k} \left\{ \frac{f_{Pg}}{C_{A,i\neq k}} \cdot \frac{\Delta c_{Ce,k,n}}{\prod\limits_{\ell=n+1}^{P} y_\ell} - \frac{\Delta y_n}{y_n} \frac{f_{Pg} \, c_{Ce,k,VPn}}{C_{A,i\neq k} \cdot \prod\limits_{\ell=n+1}^{P} y_\ell} - \frac{\Delta \phi_{k,n}}{\phi_{k,n}} \left[1 + \frac{f_{Pg} \, c_{Ce,k}}{C_{A,\, i\neq k}} \right] \right\}; [\$\text{kWh}^{-1}\text{y}]} \tag{34}$$

where $\Gamma_{A,\ i\neq k}$ and $C_{A,\ i\neq k}$ are used as before (eq. (21a) and (27a)), and where:

$$c_{Ce,k,WPn} = \sum_{p=1}^{n-1} \frac{c_{Ce,k,p}}{\prod_{\ell=p+1}^{n} y_{\ell}} \ ; \ [\$ \ m^{-2}] \tag{35}$$

expresses the fully yielded cost of the work-in-process required as input for step n in order to fabricate a unit area of output work-in-process from this step. The factor $\prod_{\ell=n+1}^{P} y_{\ell}$ is the product of the yields of the process steps subsequent to step n. The inverse of this product gives the area of work-in-process to be processed through step n in order to obtain a unit area of finished product (subsystem k). The application of eq. (34) is demonstrated on hand of an example in the next section.

Similar to the subsystem cost-effectiveness criterion $\Delta\Gamma_k$, the manufacturing process cost-effectiveness criterion $\Delta\Gamma_{k,n}$ is the product of a variable factor and the "investment per (energy per year)" ratio for the remainder of the system, in this case, however, limited to the part of the system which is based on unit area costs. The variable factor contains three terms. The first describes the influence of the difference in cost $\Delta c_{Ce,k,n}$ of the subject process options against the baseline case, or against another option, taken relative to the total cost of all other subsystems of unit area based cost. The impact of this relative cost difference is magnified by the inverse of the product of the yields of all process steps which follow the step under evaluation (n) in the process sequence up to the finished subsystem k. The second term describes the impact of the relative change in the yield of process step n which would be incurred by switching to the option being evaluated. This relative yield change is multiplied by the cost of the input work-in-process to step n, divided by the total cost of all other subsystems of unit area based costs. Again, the impact of this term is increased through the yields of all subsequent process steps. The third term finally is principally

the relative solar cell efficiency change resulting from introduction of the subject process option. The impact of this relative efficiency change is raised above unity by the ratio of the cost (per unit area) of the subsystem considered to the sum of the unit area costs of all other subsystems of area based cost structure.

Examination of eq. (34) shows that the knowledge of the "investment per (energy per year)" ratio for the remainder of the system is not needed for comparative evaluation of different process options, as this ratio is a constant factor in the cost-effectiveness criterion. This leaves only four data required as constant inputs for the evaluation: the cost of the input work-in-process; the cost of the finished subsystem; the total cost of the remaining subsystems of area based costs; and the product of the yields of the subsequent process steps. The variable inputs are the relative changes in the three key attributes of the option for the process step to be evaluated: cost, yield, and efficiency contribution. Since exact data for the four constant inputs may be difficult to obtain, intelligent estimates will sometimes be substituted. This procedure appears, at first look, appropriate as these quantities form constant multipliers. However, this approach has to be applied with caution since significant mis-estimation could shift the relative impacts of the cost, yield, and efficiency terms. This caution will be necessary in the common cases, where the cost of the finished subsystem under evaluation is small compared to the total cost of the remaining subsystems of area based cost, so that the multiplier on the relative efficiency change would not be large compared to unity.

It is clear, that the method outlined here for the solar cell manufacturing process, and expressed in eq. (34), applies equally well to the array assembly processes, except for the omission of the packing factor f_{Pg} in that case, and the replacement of the subscript Ce by subscript Ar.

Examples of Applications of the Methodology

Two examples will demonstrate the application of eq. (25) in evaluation of different design options for subsystem k.

The subsystem under consideration shall be the solar cell. The base case is a cell with a conversion efficiency of 17.5% on the basis of the solar cell area. The following relevant data for the base case are known:

Table I.

	Item	Symbol	Data	Units	Basic
1.	Solar cell price	$c_{Ce,k}$	61.38	$\$/m^2$	cell area
2.	Packing factor	f_{Pg}	0.90	--	--
	Solar cell price	$c_{A,k}$	55.24	$\$/m^2$	module area
3.	Module assembly add-on price	$c_{A,k+1}$	23.50	$\$/m^2$	module area
4.	Foundation, array assembly, installation, etc, add-on price	$c_{A,k+2}$	50.00	$\$/m^2$	module area
5.	Total area based costs	C_A	128.74	$\$/m^2$	module area
6.	Total area based costs except for subsystem k	$C_{A,i\neq k}$	73.50	$\$/m^2$	module area
7.	Module efficiency		15.75	%	module area

Problem 1.

A process is anticipated by which the efficiency of the solar cells could be raised to 20%. How much more could the solar cells cost to provide an at least equally cost-effective system?

Answer:

a) Since the subsystem of concern is of area based costs only, the second and third terms of eq. (25) are zero.

b) The subsystem k contains only cell-area based costs, designated by subscript Ce, and no array-area based costs, designated by subscripts Ar. Thus:

$$\Delta c_{Ar,k} = 0$$

$$c_{Ar,k} = 0$$

c) Since the packing factor f_{Pg} does not change with the change of cell efficiency:

$$\Delta(f_{Pg} \cdot c_{Ce,k}) = f_{Pg} \cdot \Delta c_{Ce,k}.$$

In this case, also, it is immaterial either module efficiences or cell efficiencies are used, as they are related through a constant proportionality factor.

d) Wanted is knowledge of $\Delta c_{Ce,k}$ for

$$\frac{\Delta\Gamma_k}{\Gamma_{A,i\neq k}} \leqq 0.$$

Transforming eq. (25), after applying points a) to c) above; yields then:

$$\Delta c_{Ce,k} \leqq \frac{\Delta\eta_k}{\eta_k} \left(\frac{C_{A,i\neq k}}{f_{Pg}} + c_{Ce,k} \right) . \qquad (36)$$

e) The efficiency difference $\Delta\eta_k$ going from the base case to the new subsystem option is 2.5%. All other numbers entering into the relationship given in point d) relate to the base case. Thus:

$$\Delta c_{Ce,k} \leqq \frac{+0.025}{0.175} \left(\frac{73.50}{0.9} + 61.38\right)$$

$$\leqq \underline{\underline{+\ 20.44\ \$/m^2 \text{ cell area.}}}$$

A 14% cell efficiency increase thus justifies a 33% cell cost increase for equal energy cost effectiveness, and any lower cost increase yields a more cost-effective system.

The maximum price is thus:

Base price:	61.38 $\$/m^2$ cell area
Maximum increase +	20.44 $\$/m^2$ cell area
	81.82 $\$/m^2$ cell area
Apply $f_{Pg} = 0.90$:	73.64 $\$/m^2$ module area
Module add-on cost:	23.50 $\$/m^2$ module area
Module cost	97.14 $\$/m^2$ module area

At 180 W_{pk}/m^2 output, this corresponds to 0.54 $\$/W_{pk}$.

Problem 2

In lieu of Czochralski grown wafers assumed to be used in the base case given above, the use of ribbon silicon is anticipated, resulting in a reduced cell efficiency of 14%, but an increased packing factor of 0.92. How much lower would the cell cost have to be to provide an at least equally cost effective system?

Answer:

a) Points a) and b) of answer 1 still apply.

b) As the packing factor changes,

$$\Delta(f_{Pg} \cdot c_{Ce,k}) = f_{Pg} \ \Delta c_{Ce,k} + c_{Ce,k} \cdot \Delta f_{Pg}$$

will have to be used.

c) Because of the change of packing factor, and since the energy cost determination is ultimately based on the array (or module) area related costs and efficiencies, the evaluation will have to use these latter efficiencies. For the base case, the module efficiency was 15.75%. For the option, it is 14·0.92 = 12.88%. Thus, $\Delta\eta_k = 2.87\%$.

d) Under consideration of points 2a) and 2b) above, and solving for

$$\frac{\Delta\Gamma_k}{\Gamma_{A,i\neq k}} \leqq 0,$$

as in Answer 1, eq. (25) transforms into:

$$\Delta c_{Ce,k} \leqq \frac{\Delta\eta_k}{\eta_k} \left(\frac{C_{A,i\neq k}}{f_{Pg}} + c_{Ce,k} \right) - \frac{\Delta f_{Pg}}{f_{Pg}} \ c_{Ce,k} \ ; \qquad (37)$$

e) The difference in packing factor is +0.02, compared to the base case. Outside of the efficiency difference, only data from the base case are needed:

$$\Delta c_{Ce,k} \leq \frac{-0.0287}{0.1288} \left(\frac{73.50}{0.9} + 61.38 \right) - \frac{0.02}{0.9} \cdot 61.38$$

$\Delta c_{Ce,k} \leqq -26.07 - 1.36 = -27.43$ \$/m^2 cell area

The maximum cell price for equal cost effectiveness is thus:

$$
\begin{array}{rl}
61.38 & \$/m^2 \text{ cell area} \\
\underline{-27.43} & \$/m^2 \text{ cell area} \\
33.95 & \$/m^2 \text{ cell area}
\end{array}
$$

and the corresponding module price:

Cells: 33.95 \$/m^2 $\cdot\ 0.92 = 31.23$ \$/m^2 module area

Module add-on cost $\underline{+23.50}$ \$/m^2 module area

54.73 \$/m^2 module area

At 128.8 W_{pk}/m^2 output, this corresponds to \$0.425/W_{pk} for the module.

<u>Checks to Problems 1 and 2:</u>

Try 100 kW_{pk} system:

Base case:

Area needed: $10^5\ W_{pk} : 157.5\ W_{pk}/m^2 = 632.9\ m^2$

Module price: 0.50 \$/W_{pk} $\rightarrow$ 50,000 \$

Installation etc.: 50 \$/m^2 $\rightarrow$ $\underline{31,645}$ \$

Total 81,645 \$

Option 1:

Module efficiency: 18%

Area needed: $10^5\ W_{pk} : 180\ W_{pk}/m^2 = 555.6\ m^2$

Module price 0.54 \$/W_{pk} $\rightarrow$ 54,000 \$

Installtion cost etc. 50 \$/m^2 $\rightarrow$ $\underline{27,780}$ \$

81,780 \$

Option 2:

Module efficiency 12.88%

Area needed: $10^5\ W_{pk} : 128.8\ W_{pk}/m^2 = 776.4\ m^2$

Module price: $0.425\ \$/W_{pk} \rightarrow 42{,}500\ \$$

Installation cost etc. $\$50/m^2 \rightarrow \underline{38{,}820}\ \$$

81,320 $

Problem 3

A process sequence for solar cell fabrication has been proposed by Motorola for 1986, which includes two diffusions for pn-junction and BSF layer formation. Starting with a texture-etched, cleaned wafer, a total of 5 process steps (spin-on silica front; BCl_3 diffusion; spin-on silica back, PH_3 diffusion; strip oxide both surfaces) is needed to produce a clean wafer ready for the next process step (AR coating).

RCA has proposed a completely different process sequence for cell fabrication for 1986 which includes ion implantation for both pn-junction and BSF layer formation. The conditions of the wafer before and after the 2-step process (ion-implantation, activation anneal) are equivalent to those before and after the 5-step Motorola diffusion process, except for possible differences in efficiency resulting from the two processes. Since the Motorola overall process sequence seems to be the less costly one, it will be used as the base case. Thus, in lieu of the diffusion process, ion implantation could be inserted into the base case process sequence.

Question:

One would like to know the relative cost effectiveness of the 2 competing process options for pn-junction and BSF layer formation.

Answer:

The costs and yields for the 2 process options are known, as well as the costs and yields for all the other solar cell manufacturing process steps in the base case. The cost data from the 2 companies have been normalized to the same economic base through application of the SAMICS standardized cost structure. No information is, however, available on the efficiency contributions of the 2 options. The evaluation will therefore be carried out by determining the efficiency difference which would make the 2 options equally cost-effective. Equation (34) is therefore to be solved for

$\frac{\Delta\phi_{k,n}}{\phi_{k,n}}$ for the case $\frac{\Delta\Gamma_{k,n}}{\Gamma_{k,n}} = 0$, yielding:

$$\frac{\Delta\phi_{k,n}}{\phi_{k,n}} = \left[\Delta c_{Ce,k,n} - \frac{\Delta y_n}{y_n}\, c_{Ce,k,Wpn}\right] \frac{f_{Pg}}{(C_{A,i\neq k} + f_{P_g}\, c_{Ce,k}) \prod_{\ell=n+1}^{P} y_\ell} \tag{38}$$

The information displayed in Table II is available for the base process:

Table II

	Process Step	1 Step Price* $\$/m^2$	2 Step Yield %	3 Cumul. Sub-process %	4 Yielded Step Price† $\$/m^2$	5 Sub-process Price† $\$/m^2$	6 Following Sub-process Yield %	7 Yielded Subprocess Priceϕ $\$/m^2$	8 Total Process Price $\$/m^2$
1.	Input polycrystal Si	(10 $/kg)	NA	($0.505m^2/kg$)	19.41	19.81			
2.	Sheet generation	18	($0.513m^2/kg$)	98.4	18.29				
3.	Apply etch stop back	1.24	99.4	99.0	1.25				
4.	Texture etch front	0.66	99.2	99.8	0.66				
5.	Remove etch stop back	1.58	99.8	100	1.58	41.59	86.7	47.97	
6.	Spin-on silica front	2.28	99.0	96.8	2.36		95.8		
7.	Diffuse BCl_3 back	1.94	99.0	97.8	1.98				
8.	Spin-on silica back	2.28	99.0	98.8	2.31				
9.	Diffuse PH_3 front	2.49	99.0	99.8	2.49				
10.	Strip both surfaces	0.26	99.8	100	0.26	9.40	90.5	10.39	
11.	AR coat Si_3N_4	0.93	99.2	91.3	1.02		90.5		
12.	Apply patterened r ist front	1.24	99.4	91.8	1.35				
13.	Pattern front, str;) back	0.26	99.8	92.0	0.28				
14.	Metallization	7.05	97.2	94.6	7.45				
15.	Solder coat	3.63	99.8	94.8	3.83				
16.	Electrical test	1.66	94.8	100	1.66	15.59		15.59	73.95
	Alternate Option:								
6a.	Ion implantation 2 sides	8.22	99.0	99.0	8.30				
7a.	Activation anneal	1.56	99.0	100	1.56	9.86	98.0	NA	NA

* Based on the unit area of work-in process leaving the respective process step.
† Based on the unit area of work-in-process leaving group of process steps, or sub-process.
ϕ Based on the unit area of finished product.

Table II contains all the information needed for solving eq. (38), which is summarized in Table III.

Table III

	From Table II Column	Line	Base Case	Option
$c_{Ce,k,n}$	5	10	9.40	---
	5	7a	--	9.86
$\Delta c_{Ce,k,n}$	--	--	--	+0.46
y_n	6	6	0.958	---
	6	6a	--	0.980
Δ_{yn}	--	--	--	+0.022
$c_{Ce,k}$	8	--	73.95	---
$c_{Ce,k,WPn}$	5 (divided by yield shown in column 6, Line 6)	5	43.41	---
$\prod_{\ell=n+1}^{P} y_\ell$	6	10	0.905	---
$C_{A,i\neq k}$	from Probl. 1		73.50	---
f_{Pg}	from Probl. 1		0.90	---

Thus:

$$\frac{\Delta\phi_{k,n}}{\phi_{k,n}} = \left[0.46 - \frac{0.022}{0.958} \cdot 43.41\right] \cdot \frac{0.9}{(73.5 + 0.9 \cdot 73.95)\ .0.905}$$

$$= -\ 0.0038$$

Result:

The RCA ion implantation process option thus could have an efficiency contribution 0.4% lower than that of the Motorola diffusion option, to achieve equal cost effectiveness in energy generation. The ion implantation process would thus, at equal efficiency contributions, be very slightly more cost-effective than the diffusion option, but the difference is so small that the two options really ought to be considered as equivalent.

It may also be noted that experimental results obtained at various laboratories indicate that the expectation of equal efficiency contributions from the two process options considered is justified. Thus, the result of economic equivalence of the two particular options analyzed is realistic, as far as the projections to 1986 for the various cost contributions and yields can be considered realistic.

Check:

Since the efficiency contributions are considered equal for the two competing processes, the check can be performed on the cost and yield basis alone.

Table IV

	Base Case	Option	Units
Input work in process on unit area basis	41.59	41.59	$\$/m^2$
Yield in process step	95.8	98.0	%
Needed input work-in-process for unit output work-in-process	1.044	1.02	m^2/m^2
Cost of input work-in-process	43.41	42.44	$\$/m^2$
Cost of process step per unit output work-in-process	9.44	9.86	$\$/m^2$
Cost of output work-in-process	52.85	52.30	$\$/m^2$

The option output work-in-process is thus 1% less costly. With its 0.4% lower permitted efficiency contribution, it becomes equivalent at the system level. At exact efficiency equality, it would be the (slightly) preferable process.

CONCLUSION

A quantitative comparative evaluation is frequently needed of the different design options for a particular subsystem in a photovoltaic solar energy conversion system, or of the different options for a process step in the manufacturing process sequence for such a subsystem. Such an evaluation has to be functional, which means, based on the cost of the electrical energy produced by such a system.

It is seen that such evaluations can be rather easily performed on the basis of knowledge of the quantitative differences of the key attributes of the particular option under consideration for a subsystem or a process step against the attributes of a baseline case or of a different option. The key attributes are cost and efficiency for the subsystem, assuming reliability and service life to be comparable, and cost, yield, and efficiency contribution for the process step. The other needed inputs are relatively few and of a rather fundamental nature, such as the investment needed for the whole system per unit of energy delivered annually; the total cost of the system exclusive of the subsystem being evaluated; or the cost of the input work-in-process to the particular process step being evaluated. In many instances, adequate evaluations can be performed by substituting estimated values for real data of these quantities.

It is also noteworthy that, particularly for the manufacturing process step evaluation, an analysis on the "cost per peak Watt" basis will often be adequate as a first order approximation, since the load factor which is the principal variable in the conversion to the "cost per kWh delivered" basis, is affected by the evaluation variables only through second order influences.

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3. NEW TECHNOLOGY

No new technology was developed during this quarter.